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DESIGN AND IMPLEMENTATION OF SOFTWARE ALGORITHMS FOR TOPEX/POSEIDON ONBOARD EPHEMERIS REPRESENTATIONS*

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The design and implementation of the software algorithms used to compute least squares approximations of the TOPEX and TDRS ephemerides are described. These algorithms are part of the ground support computer program OBCGEN, which generates ephemeris representations for the onboard computer (OBC). These representations are in the form of command loads that are uplinked to the TOPEX/POSEIDON satellite. The OBC software requires knowledge of the TOPEX and TDRS ephemerides to perfrom its attitude control and high gain antenna (HGA) articulation functions. Leastsquares representation of these ephemerides are used by OBC to meet memory limitaitons while satisfying both altimeter and HGA pointing accuracy requirements.

All six position and velocity components of the TOPEX state vectors spanning 10 days are represented with a least squares polynomial containing 42 coefficients each. For TDRS the three position components for both East and West satellites are represented with eight coefficients each. Scaling factors equivalent to the exponents in floating point numbers are associated with each of these coefficients.

This paper emphasizes the design and implementation of the software algorithms for the onboard ephemeris representation, Operational procedures, overall performance, and the lessons learned from operational experience are described in Ref 1.

INTRODUCTION

The TOPEX/POSEIDON onboard computer (OBC) requires knowledge of the satellite and the Tracking and Data Relay Satellite (TDRS) ephemerides to perform attitude control and high gain antenna (HGA) articulation. These ephemerides are uplinked to the satellite via the OBC Ephemeris Command Loads File, which is produced by program OBCGEN

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of the ground software Navigation Subsystem (NAVS). These OB C files are comprised of sets of coefficients and residuals for Fourier Power Series (FPS). Included are associated OBC flight times and the TOPEX satellite orbit and Earth spin rates, These FPS coefficients and auxiliary data arc used by OBC to compute the ephemerides of the TOPEX satellite and TDRSs (East and West) as functions of satellite flight time.

Ephemeris files are generated from initial states for the TOPEX satellite and each TDRS by NAVS program DPTRAJ. For input, DPTRAJ uses solution vectors of the orbit determination (OD) process as initial states supplied by the Flight Dynamics Facility (FDF) at the Goddard Space Flight Center (G SFC). OBCGEN compresses each of these ephemerides into FPS representation to conserve OBC memory while satisfying altimeter and HGA pointing accuracy requirements. A power series is computed spanning 10 days to represent each Cartesian position and veloci t y component of the satellite in t rue equator and equinox of date (TOD) coordinates. Only the position vector components of both TDRSs are represented with power series in each uplink load.

FUNCTIONAL DESCRIPTION

Figure 1 is a systems flow chart that illustrates the generation of the OBC Ephemeris Command Loads. In addition to DPTRAJ ephemeris files, inputs include general information (GIN) and planetary ephemeris files. These files supply the parameters for polar motion and timing ant] the nutations in ecliptic longitude and obliquity, respectively. To relate flight software time with UTC, OBCGEN interfaces with a Time Correlation Table supplied by the Satellite Performance Analysis Team (SPAT). Along with the least squares coefficients, optional position residuals are computed spanning a user selected 30-hour period at 10 minute centers. This option can yield greater precision during critical events. The resulting FPS coefficients, residuals, and auxiliary values are scaled and converted to their equivalent 18-bit word octal representation by emulating the numerical algorithms used by OB C. Verification of the uplinked FPS coefficients is accomplished by comparing least squares functional values with the respective DPTRAJ ephemeris values. The command syntax of the OBCG EN Ephemeris Command Loads file is validated by SPAT, and the file is uplinked to the satellite by the Telemetry, Command, and Communications Subsystem (TCCS).

This TOPEX/POSEIDON OBC ephemeris representation is based on the FPS equations inherited from LANDSAT-D (Ref 2), which invoked daily uploads spanning 37 hours each. Analysis has determined that the accuracy requirements for TOPEX/POSEIDON would be satisfied if the FPS equation domain was extended to weekly uplinks spanning 10 days (Ref 3). The following modifications to OBC and its software were necessary to accomplish this extension. The 37 hour clock was increased to 12.4 days, and the software logic was changed to allow a new range of coefficient values, And parameter was added to the uplinked file to indicate the user specified starting grid point for position residuals (spanning 30 hours at 10-min centers).

The satellite can enter a safehold mode if the ephemeris loads contain errors which cause unacceptably large point ing errors. Normal operations cease until a corrected ephemeris is uplinked. Several quality assurance steps are included in the command load generation process to reduce the possibility of uplinking a faulty ephemeris. The major quality assurance step within the OBCGEN program set is the "Verify OBC Ephemeris" process shown in Figure 1. Here, the intended OBC command loads are used to generate ephemerides (TOPEX and both TDRSs) using actual onboard algorithms. The resulting ephemerides are compared with the original ephemerides to confirm that differences are within acceptable limits. Residual plots, like those shown in Figure 2, are but one part of this thorough verification process. Figure 2 shows a typical maximum representation error of 6 mdeg, compared to the allocated requirement error of 22 mdeg.

LEAST SQUARES

For the TOPEX satellite, the form of these equations used to represent the ephemeris is a 5th degree least squares polynomial with FPS harmonic coefficients. Each Cartesian position and velocity component is represented with the following equation (Ref 2):

$$
\begin{aligned}
x(t) = {} & A_1 + tA_2 + t[A_3 + t(A_4 + t(A_5 + tA_6))] \\
& + A_7 + t[A_8 + t(A_9 + t(A_{10} + t(A_{11} + tA_{12})))] \, sin(\omega t) \\
& + A_{13} + t[A_{14} + t(A_{15} + t(A_{16} + t(A_{17} + tA_{18})))] \, cos(\omega t) \\
& + A_{19} + t[A_{20} + t(A_{21} + (A_{22} + tA_{23}))] \, sin^2(\omega t) \\
& + A_{24} + t[A_{25} + t(A_{26} + t(A_{27} + tA_{28}))] \, sin(\omega t) \, cos(\omega t) \\
& + A_{29} + t[A_{30} + t(A_{31} + tA_{32})] \, sin^3(\omega t) \\
& + A_{33} + t[A_{34} + t(A_{35} + tA_{36})] \, sin^2(\omega t) \, cos(\omega t) \\
& + [A_{37} + A_{39} \, sin(\omega t) + A_{41} \, cos(\omega t)] \, sin(2\omega_E t) \\
& + [A_{38} + A_{40} \, sin(\omega t) + A_{42} \, cos(\omega t)] \, cos(2\omega_E t)
\end{aligned}
$$

where:

$x(t)$ is any of the six cartesian position or velocity components of the inertial coordinate system;
t is the OBC flight software time relative to the reference time for the ephemeris data span;
ω is the mean orbital frequency of the satellite for the data span;
A_i (i=1,...,42) are the FPS harmonic coefficients, and
ω_E is Earth's sideral rotation frequency.

The satellite mean orbital frequency for the data span is computed from the mean semi-major axis obtained from orbit determination,

For TDRSS, each cartesian position component (both east and west) is represented with the following equation (Ref 1):

$$
\begin{aligned}
x(t) = {} & A1 + A_2 t + (A_3 + tA_4)\sin^2 \omega_E t \\
& + (A5 + tA_6)\cos \omega_E t + A7 \sin^2 \omega_E t \\
& + A8 \sin \omega_E t \cos \omega_E t
\end{aligned}
$$

where each component is determined from eight coefficients. Parameter ω_E is Earth's sideral rotation frequency.

The ephemerides are reconstructed in OBC by interpolating over grid points at 10 minute centers. The grid points are computed using the uplinked FPS coefficients, and the OBC interpolation algorithm applies the following Hermite formula (Ref 3):

$$
\begin{aligned}
y(t) &= \sum_{k=0}^{m} h_k(t) f(t_k) + \sum_{k=1}^{m} H_k(t) f'(t_k) \\
h_k(t) &= [1 - 2L'_k(t_k)(t - t_k)][L_k(t)]^2 \\
H_k(t) &= (t - t_k)[L_k(t)]^2
\end{aligned}
$$

where:
$y(t)$ is the Hermite polynomial of degree $2m - 1$, representing any position or velocity component,
m is the number of points used in the interpolation,
$f(t_k)$ and $f'(t_k)$ are any position and corresponding velocity components, and
$L_k(t)$ and $L'_k(t)$ are the Lagrangian coefficient functions and their derivatives.

NORMAL EQUATION

The least squares normal equation (Ref.4) is applied by OBCGEN to approximate ephemerides. This equation can be expressed as follows:

$$
\left(\sum_{i=1}^{p} \underline{t}_i \underline{t}_i^T \right) C = \sum_{i=1}^{p} \underline{t}_i X_i^T \tag{1}
$$

where p is the number of ephemeris points, X_i is the i^{th} DPTRAJ ephemeris vector of Cartesian position and velocity components, and C is the estimated 42 x 6 array of coefficients. Vector $\underline{t}_i$ is defined at time t_i, $i = 1, \ldots, p$, by partitioning it into harmonic factor segments as follows:

Let

$$
q_i^n = \begin{pmatrix} 1 \\ t_i \\ \cdots \\ t_i^n \end{pmatrix} \tag{2}
$$

then

$$\underline{t}_i = \begin{vmatrix} q_i^5 \\ q_i^5 \sin \omega t_i \\ q_i^5 \cos \omega t_i \\ q_i^4 \sin^2 \omega t_i \\ q_i^4 \sin \omega t_i \cos \omega t_i \\ q_i^3 \sin^3 \omega t_i \\ q_i^3 \sin^2 \omega t_i \cos \omega t_i \\ E_i \end{vmatrix} \tag{3}$$

where

$$E_i = \begin{vmatrix} \sin \omega_E t_i \\ \cos \omega_E t_i \\ \sin \omega_E t_i \sin \omega t_i \\ \cos \omega_E t_i \sin \omega t_i \\ \sin \omega_E t_i \cos \omega t_i \\ \cos \omega_E t_i \sin \omega t_i \end{vmatrix} \tag{4}$$

MEASURING TIME

The three primary measures of time used to generate OBC ephemeris command loads are Coordinated Universal Time (UTC), Ephemeris Time (ET), and OBC flight time. Being user friendly, UTC is used for user specified input times and for output listing values, Defined by the orbital motions of Earth, ET is used by DPTRAJ as the continuous independent time variable in producing the ephemerides for the TOPEX and TDRS satellites. It is dependent on the. geocentric J2000 coordinate frame, OBC flight time is generated by an onboard signal oscillator that is converted to a 48-bit counter. Three (3) 18-bit computer words contain this timing counter as a left justified 48-bit value with sign (always positive). In the OBC software, the least significant bit of this value is equivalent to $0.9765625 \mu s$ (Ref. 5).

The time span for the least squares fit is specified by the user as begin and end UTC times. Ephemeris files are read over this time span at user specified UTC time intervals to retrieve the satellite state vectors. These UTC times are converted to ET values using JPL institutional navigational software (Ref. 6). Each retrieved state vactor is tagged with its corresponding OBC flight time, which is determined using OBC versus UTC time correlation tables (Ref. 7) supplied by SPAT.

The time values t used in the least squares normal equation are scaled quantities representing OBC flight times. They are scaled so that their values lie between -1 and $+1$ as follows:

$$t = \frac{t_s - t_o}{\text{At}}$$

where

$$t_s = \text{OBC flight time}, \quad t_1 \le t_s \le t_p$$

$$t_o = \frac{t_1 + t_p}{2}$$

$$\Delta t = \frac{t_p - t_1}{2} = t_o - t_1$$

The value t_o is called the reference time, and At, the scaling factor, is the difference between t_1 and t_o, which is half the value of the specified time span. In reconstructing the ephemeris, OBC is required to subtract the reference time t_o from OBC flight times in applying the coefficients, i.e., $t = t_s - t_o$. However, the scaling factor At is factored into the uplinked coefficients A_n by OBCGEN as follows:

$$A_n = \frac{C_n}{\Delta t^n}\ , \text{ for } n = 1, \ldots, 5 \tag{5}$$

where C_n are t he least squares computed coefficients for the n^{th} power of the scaled time variable t.

SOFTWARE ALGORITHMS

The scaling Factors used in Equation (5) are computed as following:

```
      TSCALE = TEND - TREF

      DO 16 I = 2, IDIM
   16 FACT(I) = TSCALE*FACT(I-1 )
```

where FACT(1) is preset to the value 1.

The harmonic. factors for the sets of q coefficients in equation (3) are dependent On the satellite's orbital frequency R, PS(NDX). The index parameter NDX is either 1 or 2 for TOPEX or TDRS, repsectively. For each OBC flight time value TSC at 10 min centers, the following algorithm computes the corresponding set of harmonic factors:

```
      ANGL = RPS(NDX)*TSC
      SCFCN(2) = DSIN(ANGL)
      SCFCN(3) = DCOS(ANGL)
      SCFCN(4) = SCFCN(2)*SCFCN(2)

      K =4
      DO 25 I = 2, 3
      IPLUS1 = I + 1
      DP 25 J = IPLUS1, 4
      K = K + 1
   26 SCFCN(K) = SCFCN(I)*SCFCN(J)
```

The powers of time in Equation(2) for each OBC time value TSC at 10 min centers are compu t ccl as follows:

```
   T = TSC/TSCALE
   DO 30 I = 2, IDIM
30 TS(I) = T*TS(I-1)
```

where TSCALE is the scaling factor At and TS(1) is preset to the value 1. The dimension value IDIM is either 6 or 2 for TOPEX or TDRS, respectively.

The harmonic factors computed above are applied to this set of time powers as indicated in Equation (3) with the following algorithm:

```
   KPT = IDIM

   DO 40 K =2, NFCN
   KDIM = IDIM - K/4 - K/6
   DO 39 I = 1, KDIM
39 TS(I+KPT) = TS(I)*SCFCN(K)
   KPT = KPT + KDIM
40 CONTINUE
```

The value of parameter NFCN is either 7 or 5 for TOPEX or TDRS and of parameter IDIM is either 6 or 2 as defined above.

For the TOPEX satellite, Earth's orbital frequency harmonic factors E_i are included in Equation (3) as indicated in Equation (4). They are applied to TOPEX's harmonic factors with the following algorithm:

```
   ANGE =  TWOWGE*TSC
   SCGE(1) = DSIN(ANGE)
   SCGE(2) = DCOS(ANGE)

   DO 49 K = 1, 2
   DO 45 I = 1, 3
45 TS(I+KPT) = SCFCN(I)*SCGE(K)
   KPT = KPT + 3
49 CONTINUE
```

The value of KPT is continued from the above algorithm.

To apply the Normal Equation (Equat (l)), the least squares algorithm catenates the satellite's state values onto the end of the TS vector. Then the cross products of TS are computed and their sums accumulated for each OBC time as follows:

```
   DO 55 I = 1, MPLUSN
   JMAX = MIN (I,MAX)
   DO 55 J = 1, JMAX
55 SUMS(J,I) = SUMS(J,I) + TS(I)*TS(J)
```

where MPLUSN and MAX are either 48 or 11 and 42 or 8 for TOPEX and TDRS, respectively. For TOPEX the 42x6 matrix of values on the right side of the Normal Equation results from the accumulation of the st ate ant{ time cross products. Index J is greater than 42 for these cross products. Because the 42x42 matrix of values on the left side of the Normal Equation is symetrical, only t he upper right triangle of matrix values is accumulated. The lower left triangle is completed after al: the 10 min c.entered data values are processed as follows:

```
    DO 60 I  = 2, MAX
    ILESS1 = I - 1
    DO 60 J = 1, ILESS1
60  SUMS(I, J) = SUMS(J, I)
```

The same goes for TDRS with its 3x8 and 8x8 matrices.

The least squares coefficients are determined by solving the Normal Equation as a system of linear equations using JPL institutional mathematical software (Ref. 8). The resulting coefficients are rescaled to OBC time values relative to the reference time as follows (Equation (5)):

```
    ICOEFF = 0

    DO 70K = 1, NFCN
    DKIM = IDIM - K/4 - K/6

    DO 65 J = i , NSOLN
    DO 65 I = 1, KDIM
    IPLUS = I + ICOEFF
65  COEFF(IPLUSI, J) = SUMS(IPLUS, J+ MAX)/FACT(I)

    ICOEFF = ICOEFF + KDIM
70  CONTINUE
```

UPLINKED COMMAND LOADS

Three time values are incorporated into the OBC Ephemeris Command Loads File, viz,, t_{START}, t_{USE}, and δt. The time t_{START} signals OBC to compute the first four ephemeris grid points at 15 minute centers from the uplinked coefficients. Time t_{USE}, which coincides with the second grid point, identifies when OBC initiates the interpolation process using these grid points. The time interval δt <0 is the time between the first grid point and the reference time, i.e.,

$$t_o = t_1 - \delta t$$

Since the grid points are on 10 minute, i.e., 600 second, centers,

$$t_1 = t_{USE} - 600.$$

Being consistent with DPTRAJ ephemeris files, kilometers and seconds are the engineering units used in the least squares process. These units must be converted to OBC units, viz,, meters and milliseconds, for the OBC Ephemeris Command Loads File to be uplinked to the satellite.

Scale factors similar to exponents in floating point numbers are stored in the OBC memory. These scale factors position the logical binary point for the System Table '(real" parameters by multiplying by 2", where n is the scale factor, Since the hardware binary point is at the left of the most significant bit position, the scaling factor logically moves the point n bit position to the right (to the left if n < O).

Scale factors for TOPEX/POSEIDON were optimized for FPS coefficients providing a 10-day ephemeris represent at ion. Experience has shown that numerical problems somet imes occur when these scale factors were used to generate ephemerides less than 6 clays (near maneuvers, for example). Overflow causing loss of the most significant bit occurs because the scale factors no longer accommodate the required FPS coefficients. As a result, a standardized 10-day ephemeris is always utilized regardless of the mission activity, for it is operationally impractical to also determine and uplink new scale factors with each ephemeris command load.

INPUT PARAMETERS

Input parameters and options are entered into OBCGEN using Fortran's Namelist. The following table lists these Namelist inputs ant] their default values if applicable:

$OBC Namelist Parameters

Symbol	Type	Description
OPTION	A*5	Satellite indicator ('TOPEX','TDRS', or 'BOTH')
BEGT	A*24	Begin time (UTC) of fit in ATB format
ENDT	A*24	End time (UTC) of fit in ATB format
DMINS	DP	Time interval (rein) between sampled DPTRAJ Ephemeris state vectors
DTUSE	DP	Time interval (rein) Let ween t_{START} and t_{USE}.
RSTART	I	Grid number at which residuals start (=2)
SMA	DP	Mean semi-majcw axis of TOPEX satellite's orbit (km).
GM	DP	Earth's gravitational constant (km^3/sec^2).
WGE	DP	Earth's spin rate (rev/s)
DEVICE	A*12	Plot device (e.g., 'CPS/PS')(See PGPLOT UG).
FILENR	I	Version number for uplink coefficient file (IO).

PGTORS	L	TDRS residual plot sfotware (T = plots; F = no plots).
TBEDSW	L	Output files for test heel software (T = files; F = no files).
BUFSW	L	Tweak software for OBC software error (sets least significant 18-bit work of tripple precision number to non-zero value).

REQUIRED FILES

The following files are required to execute OBCGEN.

File	I/O	Description
OOE	I	TOPEX satellites DPTRAJ ephemeris
TDRSE	I	TDRS/East 13 PTRAJ ephemeris
TDRSW	I	TSRS /West DPTRAJ ephemeris
12	I	Planetary ephemeris
GIN	I	General astrodynamic information
FOR035	I	UTC to OBC time correlation table
FOR036	I	OBC to UTC time correlation table
PR_OBC	O	Printer output listing
CPS.PS	O	Residual plots
OBC File	O	OBC Ephemeris Command Loads (File name and content are generated by OBCGEN.)

013C EPHEMERIS COMMAND LOADS

System tables 33 and 34 are the Ephemeris Command Loads for the TOPEX satellite and TDRSs, respectively. The parameters in these tables arc defined in Tables 1 and 2. In the fourth column under the header '2**n' are the scaling factors used by OBC for these parameters. The scaling factors for the TOPEX coefficients, arc listed in Table 3.

Table 1. System Table 33 for Satellites Ephemeris

WORD	NAME#	TYPE	2**n	DESCRIPTION	UNIT
1	NEWDATA	I	-	Indicator for OBC to use table values. Initialized at O.	
2-4	TSTART	D+	38	OBC timo to calculate grid point values (1 min before TUSE).	ms
S-7	TUSE	D+	38	OBC time to use table values (= time of grid point 2).	ms
8	RSTART	I	-	Starting grid number of residual data.	
9-10	EIGWTIST	D	30	Time interval of 1st grid point past FPS reference time .a.	ms
11	EIGVNTMX	I	-	Maximum number of residual points.	
12	EIGVNT	I	-	Number of poeition residual points.	
13-14	EIGWWFS	D	-21	Satellite)e orbital frequency.	rev/ins
15-16	EIGW2ND	D	-2s	Two times Earth's spin rate.	rev/ins
17-268	EIGBA	D(3,42)	*	FPS coefficient array for TOPEX position (x,y,z).	m
269-520	EIGBA	D(3,42)	*	FPS coefficient array for TOPEX velocity (x,y,z).	m/ms
621-1060	EIGBRES	E(3,180)		TOPEX position residual array (10 min center)	m

From Document 96S-ER1OO1 for consistency.

* The two's exponent values (scaling factor) for FPS position and velocity arc specified in Table 3.

$.a = t_0$

NOTE: Integer and single, double, and triple precision fixed point numbers are type I, E, D, and D+, respectively.

Table 2. System Table 34 for TDRS Ephemerides

WORD	NAME#	TYPE	2**n	DESCRIPTION	UNIT
1	NEWDATAT	I	-	Indicator for OBC to use table values. Initialized at 0.	
2-4	TSTARTT	D+	38	OBC time to calculate grid point values (1 min before TUSE).	ms
5-7	TUSET	D+	38	OBC time to use table values.	ms
8-9	EIGWTTI	D	30	Time interval of 1st grid point past FPS reference time .a.	ms
10-11	EIGWTTL	D	30	Time interval of last grid point from FPS reference time .a.	ms
12-13	EIGWWTE	D	-25	Orbital frequency of TDRS East.	rev/ins
14-16	EIGWWTW	D	-25	Orbital frequency of TDRS West.	rev/ins
16-63	EIGBBE	D(3,8)	*	FPS coefficients for TDRS East position (x,y,z).	m
64-111	EIGBBW	D(3,8)	*	FPS coefficients for TDRS West position (x,y,z).	m

From Document 968-ER1OO1 for consistency.

NOTE: Integer and single, double, and triple precision fixed point numbers are t ype 1, E, D, and D+, respectively.

* Exponent is 26 for all coefficients except for those whose second subscript is 2, 4, or 6. In these cases, the exponent is –2.

.a = t_0

Table 3. TOPEX FPS Cocffic.tint Scaling Factors (n)

	2**n			2**n	
INDEX	POSITION	VELOCITY	INDEX	POSITION	VELOCITY
1	23	3	24	23	3
2	-7	-27	25	-7	-27
3	-38	-58	26	-38	-58
4	-69	-89	27	-69	-89
6	-99	-119	28	-99	-119
6	-129	-149	29	23	3
7	23	3	30	-7	-27
8	-7	-27	31	-38	-58
9	-38	-58	32	-69	-89
10	-69	-89	33	23	3
11	-99	-119	34	-7	-27
12	-129	-149	35	-38	-58
13	23	3	36	-69	-89
14	-7	-27	37	13	-7
15	-38	-58	38	13	-7
16	-69	-89	39	13	-7
17	-99	-119	40	13	-7
18	-129	-149	41	13	-7
19	23	3	42	13	-7
20	-7	-27			
21	-38	-58			
22	-69	-89			
23	-99	-119			

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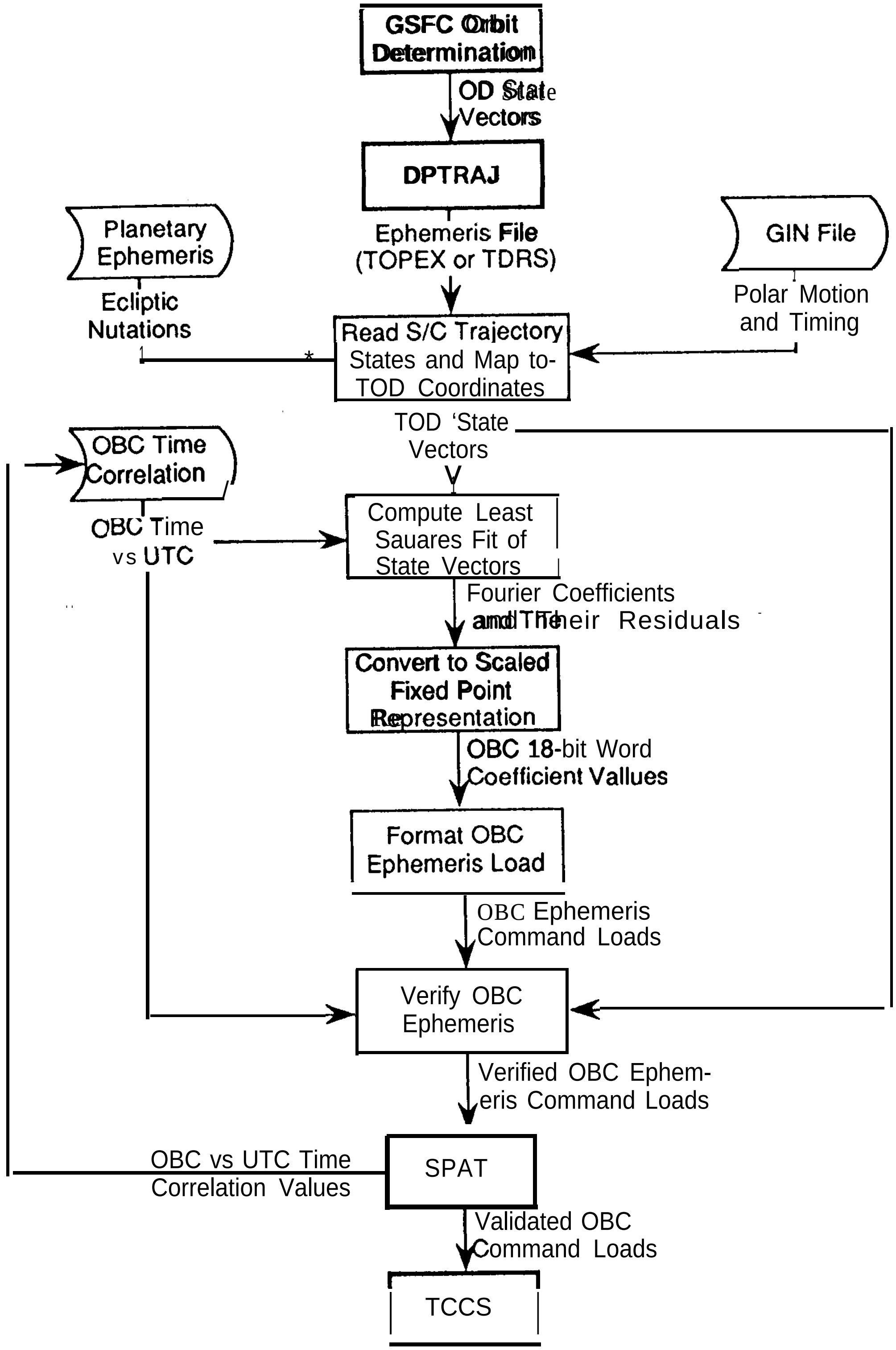

Figure 1. OBCGEN System Flow Chart

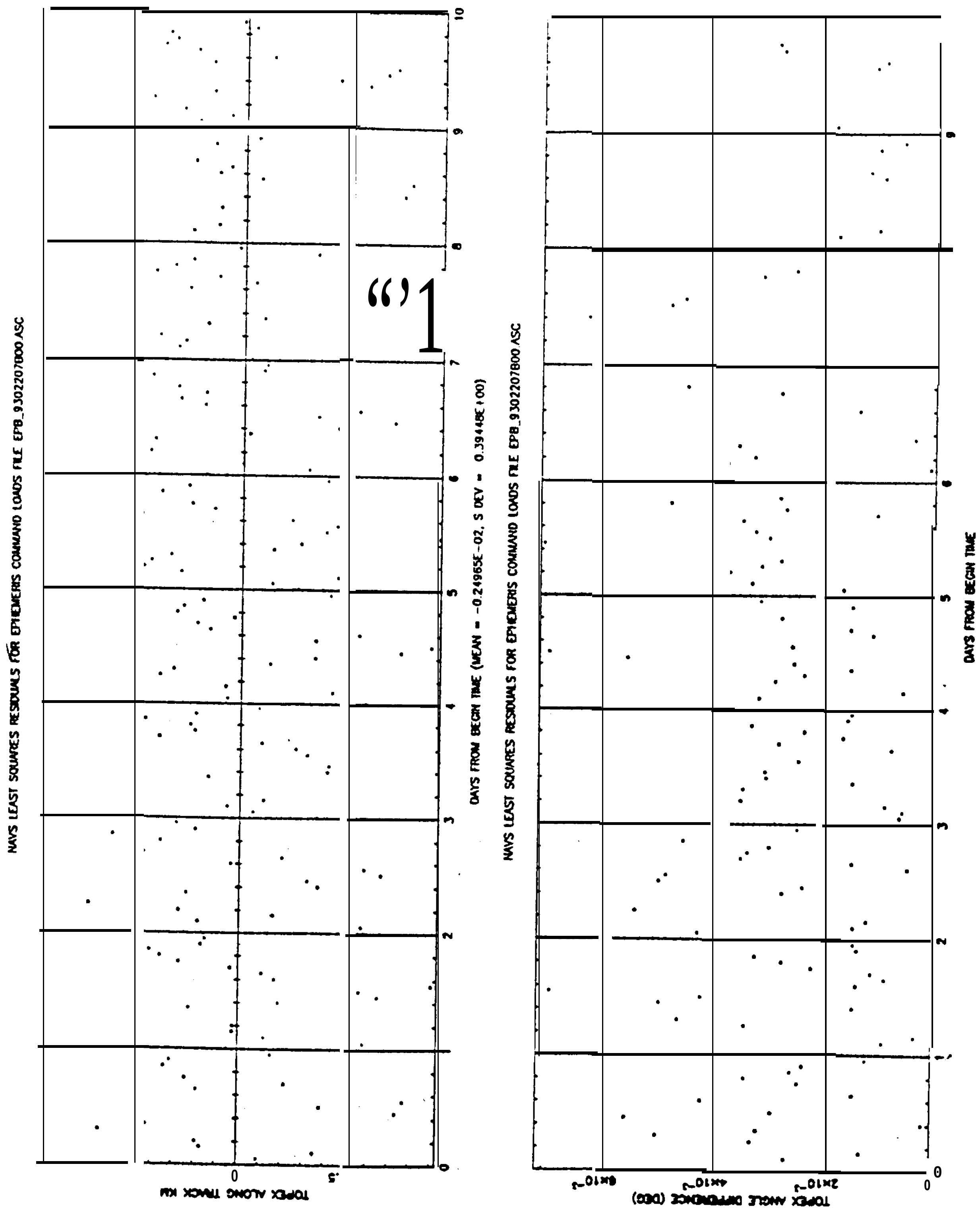

Figure 2. Pointing Error Verification